The Antioxidant Effect of Natural Substances on Lipids During Irradiation of Chicken Legs

A. Mahrour[a,b], S. Caillet[a,b], J. Nketsia-Tabiri[c], and M. Lacroix[a,b,*]

[a]Canadian Irradiation Center (CIC) and [b]Research Laboratory in Sciences Applied to Food, INRS-Institut Armand-Frappier, Université du Québec, Laval, QC, H7V 1B7, Canada, and [c]Ghana Atomic Energy Commission, Legon, Ghana

ABSTRACT: Entire fresh chicken legs were subjected to three pretreatments (packaged in air; packaged under vacuum; or marinated in natural plant extracts and packaged in air) followed by irradiation (0, 3, or 5 kGy). The control and irradiated chicken legs were stored at 4°C and analyzed for FA composition and sensory quality at predetermined intervals. Irradiation dose had a significant ($P \leq 0.01$) effect on FA derived from phospholipid but less than on FA derived from a neutral lipid. In general, levels of unsaturated FA decreased as the radiation dose increased; however, for marinated chicken legs irradiated with 5 kGy, levels of linoleic acid ($C_{18:2}$) and arachidonic acid ($C_{20:4}$) derived from the phospholipid fraction were significantly ($P \leq 0.05$) higher than those irradiated in air or under vacuum. The concentration of FA also decreased significantly ($P \leq 0.05$) as storage time increased. For chicken legs packaged in air or marinated and then packaged in air, significant ($P \leq 0.01$) inverse correlations existed between high-carbon-number PUFA and lower-carbon-number (≤17) saturated FA; this relationship was not apparent in samples irradiated under vacuum. A processing combination of marinating and vacuum packaging might better control lipid oxidation and degradation in irradiated chicken. Panelists found no significant difference ($P > 0.05$) in the flavor and odor intensity of cooked irradiated chicken legs and their nonirradiated equivalents.

Paper no. J10333 in *JAOCS 80,* 679–684 (July 2003).

KEY WORDS: Antioxidants, extracts from plant spices, fatty acids, irradiation, poultry.

Antioxidants are widely used to stabilize fats and control oxidative deterioration of foods. Most of the antioxidants in use commercially (e.g., BHA, BHT, TBHQ, and propyl gallate) are synthetic (1). Although largely effective, synthetic antioxidants continue to be scrutinized for their safety as food additives; consequently, there is increasing public interest in the use of natural antioxidants. Extracts from spices, rosemary, thyme, and sage are reported to possess antioxidant properties comparable to or greater than BHA and BHT (2). Lacroix *et al*. (3) reported that natural antioxidants from rosemary and thyme caused substantial reduction in the generation of volatile hydrocarbons from arachidonic and linoleic acids generated during irradiation at 3 and 9 kGy. Antioxidant properties of these spices have been attributed to their phenolic compounds and the essential oil fraction (4). Citric acid, a naturally occurring substance, contributes to the stability of lipids by chelating metals (e.g., iron and copper), which act as pro-oxidants. The use of natural antioxidants could be effective in protecting food nutrients against oxidation and at the same time could enhance the effectiveness of irradiation technology by reducing the dose necessary to eliminate pathogenic bacteria in food (5). However, irradiation of meat enhances lipid oxidation, resulting in the development of undesirable flavors (6,7). Radiolytic hydrocarbons, the major products of lipid oxidation, contribute to undesirable off-flavors in irradiated meats. Merritt *et al.* (6) found that irradiation dose was linearly related to production of radiolytic hydrocarbons. There appears to be a threshold dose above which off-flavors are detected in irradiated meats; for poultry, the threshold dose was reported to be 2.5 kGy (8). Indications are, however, are that doses higher than 2.5 kGy may be required for complete elimination of *Salmonella* on chicken (9).

The objective of this study was to evaluate the effects of three treatments—(i) marinating in natural plant extracts prior to irradiation; (ii) irradiating in air; (iii) irradiating under vacuum—on FA composition and sensory quality of entire fresh chicken legs during storage at 4°C.

EXPERIMENTAL PROCEDURES

Chicken legs. Entire fresh chicken legs (150 ± 50 g each) were purchased at a local grocery (IGA, Laval, Canada) on the day of slaughter and prepared in three different ways: packaged in air; packaged under vacuum; or marinated and packed in air.

Marinating. The marinade was a mixture of 250 mL of lemon juice, 20 g of ground thyme, and 20 g of ground rosemary. The entire chicken legs were immersed in the marinade (in a ratio of 12 legs per liter) for 24 h at 4°C so as to reduce the pH (2.76) and solubilize active compounds present in the spices.

Packaging. Chicken legs were individually packed with high-barrier Cryovac BBI bags (Duncan, SC) and sealed in air or under vacuum according to the assigned pretreatment before irradiation. The thickness of the bag film was 50 μm, and O_2 and CO_2 permeability values were 20 and 80 $cm^3\ m^{-2}\ day^{-1}\ atm^{-1}$, respectively. A Multivac model A300 machine (Haggenmuller, Wolfertschwenden, Germany) was used for the sealing.

Irradiation. The individually packaged entire fresh chicken legs were placed in iced styrofoam boxes (17″ × 11″ × 6″) and

*To whom correspondence should be addressed at Research Laboratory in Sciences Applied to Food, INRS-Institut Armand-Frappier, Université du Québec, Laval, QC, H7V 1B7, Canada.
E-mail: monique.lacroix@inrs-iaf.uquebec.ca

loaded in the JS8900 carrier-type irradiator (MDS Nordion International, Kanata, Ontario, Canada) with a cobalt-60 source. The dose range was from 2.9 to 3.4 kGy for a mean dose of 3 kGy, and 4.8 to 5.3 kGy for a mean dose of 5 kGy. Amber perspex 3042D (Atomic Energy Research Establishment, Harwell, Oxfordshire, United Kingdom) was used to validate dose distribution within the boxes. Both irradiated and nonirradiated chicken legs were stored at 4°C.

Extraction of lipids. Whole chicken legs were ground, and duplicate aliquots (5000 ± 0.1 mg) were subjected to lipid extraction sequentially by the dry column method (10). The sample was ground in a mortar with 20 g granular anhydrous sodium sulfate and then with 15 g Celite 545 (Fisher Scientific, Ltd., Ottawa, Canada). The resulting mixture was packed onto 10 g of 1:9 $CaHPO_4$/Celite 545 trap in a glass chromatography column (i.d. 35 mm). The column was charged with 90:10 CH_2Cl_2/MeOH (Anachemia, Rouses Point, NY) and 150 mL of eluate was collected into a 200-mL round-bottomed flask. Solvent was removed by evaporation under nitrogen at room temperature, and the contents of the flask were transferred with hexane into 100-mL volumetric flasks and brought to volume with hexane.

Separation of neutral lipids (NL) and phospholipids (PL). Total lipids were separated into NL and PL according to the method of Salih *et al*. (11). Lipid fractions (0.5 g) were held for 16 h at −25°C in a 125-mL Erlenmeyer flask containing 10 g activated silicic acid (Sigma Chemical Co., St. Louis, MO) and 125 mL chloroform (Anachemia). The content of each flask was filtered through a sintered glass funnel under vacuum. The silicic acid remaining in the funnel was washed with 5 × 30 mL aliquots of chloroform to elute the NL. The PL were eluted by washing the silicic acid residue with 3 × 25-mL aliquots of methanol. The solvents were evaporated under nitrogen from each fraction; the PL or NL were weighed and redissolved in chloroform to a specified volume.

Derivatization of glycerides to methyl esters. The NL or PL were converted to their methyl esters according to the method of Slover and Lanza (12). The lipids were treated with NaOH/MeOH followed by BF_3/MeOH. Methyl heneicosanoate ($C_{21:0}$) was added as internal standard.

Equipment. A Varian Model 3400 gas chromatograph, equipped with a hydrogen FID, Varian Star Chromatography Workstation software (1992), and 30 m × 0.25 mm i.d., 1-μm film thickness DB5 capillary column (Supelco Inc., Bellefonte, PA) was used. Helium was used as carrier gas. The column temperature was held for 1 min at 80°C and then increased at 20°C/min to 150°C and then at 4°C/min to 280°C. The injector temperature was increased from 70 to 300°C at 100°C/min and held for 60 min. The detector temperature was maintained at 300°C.

Identification. FA of NL and PL were identified by comparison with standards and the retention times of known FAME peaks. The FA standards were obtained from Aldrich Chemical Co. (Milwaukee, WI), and the PL standards were obtained from Sigma (Sigma). Peak areas were quantified by the computer (Varian Star Workstation) using integration parameters and expressed as percentages of total area.

Sensory evaluation. Thirty panelists from the INRS-Institut Armand Frappier (Laval, QC, Canada) who evaluated the sensory attributes of the cooked entire fresh chicken legs had previously participated in training sessions to become familiar with the sensory characteristics of cooked entire fresh chicken legs. Panelists were trained for a period of 3 mon in 1-h sessions three times a week (36 h total). Triangle tests were performed for each session (13 h total) to select 10 panelists who could detect off-flavors in chicken irradiated with 7, 5, or 3 kGy. Prior to sample evaluation, these 10 selected panelists participated in 2–3-h orientation sessions to select, recognize, and scale attributes of chicken using references and an intensity scale. The panel agreed on all attributes considered necessary for evaluation of the irradiated chicken and defined theses attributes. Panelists were asked to evaluate the color intensity, the flavor intensity, the odor intensity, and the muscle fiber integrity (mushiness) of the samples on the instruction scaling by making a vertical line across the scale to reflect their judgment. The instruction scaling is composed of a 15-cm-long horizontal line, anchored with a term at each end, containing graduations every 1.5 cm (13). For each attribute, the distance was measured in centimeters with a ruler from the left end point to the point marked by the panelist, and the numerical score was recorded. The terms from the left end to the right end were, respectively, none and strong for odor, pale yellow to dark yellow for color, no off-flavors to intense off-flavors for flavor, and tough to tender for muscle fiber integrity.

The day after irradiation (5 kGy), 60 entire fresh chilled bone-in chicken legs (20 packed in air, 20 packed under vacuum, and 20 marinated, packed in air) were roasted in a conventional oven at 190°C until the internal temperature reached 82–85°C before being served to the panelists. After cooking, roasted chicken legs were covered with aluminum foil and held in an oven at 77°C until served on white polyfoam plates. Samples were presented in random sequence to panelists. The serving size was an entire cooked chicken leg, and samples were served with the skin. Evaluation was conducted in an air-conditioned sensory evaluation laboratory in individual partitioned booths. Each booth was illuminated with an 80-watt incandescent bulb. Samples were identified by a three-digit code number. Panelists were instructed to evaluate color of the entire sample first and odor second, and then to remove the leg and skin. Panelists cut a strip from a specific part of the leg and cut it into cubes; these cubes were used for flavor and muscle fiber integrity evaluation. Water and unsalted crackers were provided for cleaning the palate between samples.

Experimental design and statistical analysis. A 4 × 3 × 3 × 6 randomized complete block design representing 4 replicates, 3 pretreatments, 3 radiation dose levels, and 6 storage times was used for this study. The responses measured were the concentration (%) of the FA derived from either the NL or the PL fraction of the chicken legs. Multifactor ANOVA was performed on the data using Stat-Packets computer software (Stat-Packets, 1987 version; Walonik Associates, Minneapolis, MN) to yield ANOVA summary tables, treatment means, and SD. The same statistical software was used to generate correlation coefficients and regression equations. Fisher's LSD was used

to analyze differences between means. In all cases, P values ≤0.05 were considered to be significant.

RESULTS AND DISCUSSION

The results indicated that the major FA in both the NL and PL fractions of the entire fresh chicken legs were oleic acid ($C_{18:1}$), palmitic acid ($C_{16:0}$), linoleic acid ($C_{18:2}$), and stearic acid ($C_{18:0}$), in decreasing order of concentration, i.e., 48, 25, 11, and 5%, respectively, in the NL fraction and 27, 23, 17, and 13% in the PL fraction (data not shown). Note that the concentration of oleic acid (48%) in the NL fraction was nearly twice that in the PL fraction. PUFA that were identified included linolenic acid ($C_{18:3}$), eicosadienoic acid ($C_{20:2}$), eicosatrienoic acid ($C_{20:3}$), and arachidonic acid ($C_{20:4}$). The PL fraction had higher levels of linolenic acid and eicosatrienoic acid than the NL fraction. The content of $C_{18:3}$, $C_{20:2}$, $C_{20:3}$, and $C_{20:4}$ in the NL fraction was, respectively, 0.2, 2.6, 0.8, and 6%, and in the PL fraction was, respectively, 5, 2, 3, and 6% (data not shown).

Effect of process variables on FA. Inspection of the ANOVA summary in Table 1 suggested that levels of FA derived from the PL fraction were significantly ($P \leq 0.01$) affected by the pretreatments, radiation doses, and storage times. The concentrations of FA derived from the NL fraction, however, were influenced by variations in the pretreatments and storage time, but less so by variations in radiation dose (Table 1). The results further indicated significant ($P \leq 0.01$) interactions between the variables. With the exception of eicosadienoic acid ($C_{20:2}$), all the FA derived from the PL fraction were significantly affected ($P \leq 0.05$) by interactions between radiation dose and pretreatment (Table 1).

Effect of pretreatments. The effects of the pretreatments on FA derived from NL and PL were dependent on the FA and the source of the FA (Table 2). For example, palmitoleic acid ($C_{16:1}$) from the NL fraction of chicken treated under vacuum was present at a significantly ($P \leq 0.05$) lower average concentration of 8.92% (Table 2) than in chicken treated in air (9.74%) or marinated (10.65%). For linoleic acid ($C_{18:2}$), also derived from the NL fraction, samples treated in air had a significantly ($P \leq 0.05$) higher average concentration (10.53%) than that observed from marinated chickens (9.91%). Contrary to what was observed for linoleic acid derived from the NL fraction, the average concentration of linoleic acid derived from the PL fraction was significantly ($P \leq 0.05$) higher (17.73%) when the chicken was marinated than when treated under vacuum (16.90%) or in air (14.80%). Levels of arachidonic acid also were highest in marinated chicken. Rady *et al.* (14) reported that packaging in air or under vacuum had little effect on the FA profiles of neutral and polar lipids separated from chicken tissues irradiated with doses between 1 and 10 kGy. Lacroix *et al*. (3) reported that natural antioxidants from rosemary and thyme caused substantial reduction in the generation of volatile hydrocarbons from unsaturated arachidonic and linoleic acids during irradiation at 3 and 9 kGy. Rosemary (*Rosmarinus officinale* L.) contains antioxidant substances (2,4). The results of our study suggest that the antioxidant effect of natural substances, present in the marinade, on lipids in a complex material (chicken muscle) was different from that on isolated lipids. The natural substances in the marinade exerted a greater antioxidant effect on lipids derived from PL than on NL. It has been reported that PUFA, notably arachidonic acid of the PL fraction, decrease appreciably during lipid oxidation and storage (15,16).

Effect of radiation dose. The concentration of FA derived from the PL fraction was influenced more by variations in the radiation dose than the FA derived from the NL fraction (Table 1). In general, the concentration of unsaturated FA decreased

TABLE 1
Summary Table (F' values) for Multifactor ANOVA

Source of variation		Dependent variables: FA from phospholipid fraction in chicken legs										
		$C_{14:1}$	$C_{16:0}$	$C_{16:1}$	$C_{18:0}$	$C_{18:1}$	$C_{18:2}$	$C_{18:3}$	$C_{20:0}$	$C_{20:2}$	$C_{20:3}$	$C_{20:4}$
Independent variables												
MA[a]:	Storage time (d)	18.57[b]	45.92[b]	4.28[b]	12.70[b]	0.96	38.51[b]	151.27[b]	10.76[b]	9.90[b]	184.46[b]	10.73[b]
	Radiation dose (kGy)	10.02[b]	214.96[b]	1.85	151.46[b]	29.50[b]	264.52[b]	230.22[b]	85.78[b]	37.13[b]	44.30[b]	52.49[b]
	Pretreatment	75.45[b]	332.09[b]	19.16[b]	206.13[b]	39.65[b]	783.09[b]	76.50[b]	56.89[b]	17.87[b]	11.29[b]	116.02[b]
In[c]:	Storage time/dose	0.69	2.90	0.58	0.55	1.98	1.91	20.10[b]	1.28	3.71[b]	17.29[b]	1.56
	Dose/pretreatment	6.62[b]	40.59[b]	11.98[b]	21.80[b]	8.91[b]	29.91[b]	10.99[b]	5.49[b]	2.26	8.24[b]	3.91[b]
	Storage time/pretreat.	5.95[b]	7.84[b]	0.24	1.59	0.59	1.39	7.18[b]	6.45[b]	1.64	33.40[b]	0.38

Source of variation		FA from neutral lipid fraction in chicken legs								
		$C_{14:0}$	$C_{14:1}$	$C_{16:0}$	$C_{16:1}$	$C_{18:0}$	$C_{18:1}$	$C_{18:2}$	$C_{18:3}$	$C_{20:0}$
Independent variables										
MA[a]:	Storage time	0.65	4.34[b]	13.46[b]	84.38[b]	5.23[b]	28.23[b]	69.76[b]	8.06[b]	7.30[b]
	Radiation dose	12.06[b]	2.86	0.82	20.93[b]	1.51	2.09	3.06	0.41	4.93
	Pretreatment	15.93[b]	1.29	33.58[b]	495.60[b]	4.48	12.39[b]	64.06[b]	0.27	1.47
In[c]:	Storage time/dose	1.22	1.60	0.52	2.18	0.64	1.19	0.70	0.65	2.06
	Dose/pretreatment	0.52	1.78	8.89[b]	13.66[b]	0.88	5.17[b]	6.34[b]	0.82	1.27
	Storage time/pretreat.	0.73[b]	1.48[b]	0.95	3.57[b]	0.57	1.18	8.78[b]	0.70	2.01

[a]MA: main effects.
[b]($P \leq 0.01$).
[c]In: Interactions.

TABLE 2
Treatment Means[a] Showing the Effects of Irradiation in Air, Vacuum, or Marinade on FA from Neutral Lipids (NL) and Phospholipids (PL) in Chicken Legs

	Pretreatments		
FA	Air	Vacuum	Marinade
$C_{16:1}$ (NL)	9.74 ± 0.73A	8.92 ± 0.55B	10.65 ± 0.35C
$C_{18:1}$ (NL)	47.78 ± 0.65A	48.29 ± 0.73B	48.03 ± 0.45C
$C_{18:2}$ (NL)	10.53 ± 0.53A	10.49 ± 0.78A	9.91 ± 0.28B
$C_{16:1}$ (PL)	6.70 ± 0.72A	5.79 ± 0.78B	6.01 ± 0.35B
$C_{18:1}$ (PL)	26.52 ± 1.55A	27.04 ± 0.93B	25.19 ± 0.53C
$C_{18:2}$ (PL)	14.80 ± 1.24A	16.90 ± 1.02B	17.73 ± 0.45C
$C_{20:4}$ (PL)	2.11 ± 0.15A	3.55 ± 0.21B	4.81 ± 0.37C

[a]Means in a row bearing the same letter are not significantly different ($P > 0.05$).

with increasing radiation dose; conversely, the concentration of saturated FA increased with increasing radiation dose. For example, the concentrations of palmitic acid ($C_{16:0}$) and stearic acid ($C_{18:0}$) increased from 23.40 and 12.74%, respectively, to 24.82 and 14.49% when the radiation dose increased from 0 to 5 kGy (Table 3). The levels of oleic acid (27.17%) and linoleic acid (17.38%), however, were significantly ($P \leq 0.05$) higher in the nonirradiated chicken than the 25.59 and 15.62%, respectively, present in chicken irradiated with 5 kGy. Hassan and Shams (16) also reported an inverse relationship between unsaturated FA and radiation dose. The significant ($P \leq 0.01$) interactions between radiation dose and pretreatment (Table 1) suggest that the effect of radiation dose on the concentration of FA was dependent on the pretreatment. For linoleic acid derived from the PL fraction, the extent of loss induced by increasing the radiation dose was less in marinated chicken, 18.10% (0 kGy), 17.60% (3 kGy), and 17.50% (5 kGy) (data not shown), than in chicken irradiated in air (16.10, 14.70, 13.60%, respectively) or irradiated under vacuum (17.90, 17.00, and 15.60%, respectively).

Effect of storage time. The concentration of FA derived from NL or PL was influenced by variations in the storage time (Table 1). In general, the concentration of FA decreased with an increase in storage time. For example, linoleic acids derived from the PL fraction decreased significantly ($P \leq 0.05$) from 17.09% on day 1 to 15.82% on day 15 (data not shown). A similar trend was followed by linoleic acid derived from the NL fraction. Hassan and Shams (16) also reported a decrease in the concentration of unsaturated FA in irradiated meat with an increase in storage time.

Correlation between the FA. A significant ($P \leq 0.01$) correlation between the FA was observed (Table 4). The trends followed by the correlation coefficients between the FA under two of the pretreatments (air and marinade) were similar, but different from that followed by FA in chicken meat treated under vacuum. An important observation is the inverse relationship between the content of linoleic acid ($C_{18:2}$), linolenic acid ($C_{18:3}$), eicosadienoic acid ($C_{20:2}$), eicosatrienoic acid ($C_{20:3}$), and arachidonic acid ($C_{20:4}$), derived from chicken legs irradiated in air or marinade and the lower-carbon-number (≤17) saturated FA. Such inverse correlation between these PUFA and lower-carbon-number saturated FA was not apparent in vacuum-treated chicken legs. The results suggested that irradiation under vacuum suppressed scission of high-carbon-number unsaturated FA into lower-carbon-number (≤17) saturated FA. A combination of marinating and vacuum packaging might be a better approach for controlling lipid oxidation and degradation than either process alone during irradiation of chicken.

Predictive models based on radiation dose and storage time. Predictive models for most of the FA based on radiation dose and storage time were significant ($P \leq 0.01$). The models for linoleic and linolenic acids are shown in Table 5. The coefficient of determination (R^2) for the models ranged between 0.78 and 0.95. The models suggested that both radiation dose and storage time were inversely related to the FA concentration.

Effects of pretreatments and irradiation on the sensory quality of chicken legs. Panelist scores for odor intensity, flavor intensity, color intensity, and muscle fiber integrity were neutral for both the control and irradiated samples (Table 6). For chicken legs irradiated in air, scores for odor intensity (7.8) and flavor intensity (8.7) were significantly ($P \leq 0.05$) higher than the controls (6.1 for odor intensity and 6.9 for flavor intensity), but there was no significant difference ($P > 0.05$) between the

TABLE 3
Treatment Means[a] Showing the Effects of Radiation Dose on Some FA Derived from PL in Chicken Legs

	Radiation doses		
FA	0 kGy	3 kGy	5 kGy
$C_{16:0}$	23.40 ± 0.76A	23.86 ± 1.35A	24.82 ± 0.83B
$C_{18:0}$	12.74 ± 0.73A	13.55 ± 1.20B	14.49 ± 1.12C
$C_{18:1}$	27.17 ± 1.33A	25.99 ± 1.24B	25.59 ± 0.84C
$C_{18:2}$	17.38 ± 1.04A	16.44 ± 1.42B	15.62 ± 1.69C

[a]Means in a row bearing the same letter are not significantly different ($P > 0.05$). For abbreviation see Table 2.

TABLE 4
Correlation Coefficients for FA from PL of Chicken Legs Irradiated in Air, Vacuum, or Marinade

		$C_{14:0}$	$C_{14:1}$	$C_{15:0}$	$C_{16:0}$	$C_{16:1}$	$C_{17:0}$	$C_{18:0}$	$C_{18:1}$	$C_{18:2}$	$C_{18:3}$	$C_{20:0}$	$C_{20:2}$
Air	$C_{18:2}$	–0.89[a]			–0.81[a]	–0.61[a]		–0.89[a]					
	$C_{18:3}$	–0.65[a]		–0.64[a]	–0.88[a]	–0.76[a]	0.68[a]	–0.77[a]		+0.79[a]			
	$C_{20:2}$	–0.60[a]		–0.64[a]	–0.87[a]	–0.76[a]	0.68[a]	–0.76[a]		+0.77[a]	+0.98[a]		
	$C_{20:3}$		+0.70[a]	–0.87[a]	–0.65[a]	–0.61[a]	0.91[a]				+0.69[a]		+0.71[a]
	$C_{20:4}$	–0.70[a]			–0.75[a]	–0.79[a]		–0.78[a]		+0.79[a]	+0.93[a]		+0.89[a]
Vacuum	$C_{18:2}$	–0.82[a]		–0.83[a]	–0.76[a]		–0.69[a]	–0.91[a]	+0.74[a]				
	$C_{18:3}$								+0.78[a]				
	$C_{20:2}$								+0.64[a]				
	$C_{20:3}$								+0.74[a]	+0.99[a]			
	$C_{20:4}$							+0.68[a]	+0.83[a]	+0.92[a]		+0.91[a]	
Marinade	$C_{18:2}$	–0.61[a]		–0.65[a]			–0.60[a]	–0.59[a]	+0.66[a]				
	$C_{18:3}$	–0.72[a]	+0.74[a]	–0.76[a]	–0.70[a]		–0.75[a]	–0.68[a]	+0.62[a]	+0.89[a]			
	$C_{20:2}$	–0.77[a]		–0.72[a]	–0.78[a]		–0.73[a]	–0.77[a]	+0.76[a]	+0.82[a]	+0.86[a]		
	$C_{20:3}$		–0.63[a]							+0.81[a]			
	$C_{20:4}$	–0.92[a]		–0.68[a]	–0.90[a]		–0.68[a]	–0.91[a]	+0.87[a]	+0.68[a]	+0.78[a]	–0.62[a]	+0.72[a]

[a]($P \leq 0.01$). For abbreviation see Table 2.

scores for color intensity and muscle fiber integrity (Table 6). For chicken legs that were marinated or vacuum treated, no significant difference ($P > 0.05$) was observed between the mean scores for all the sensory quality attributes tested. Irradiation in the absence of oxygen (vacuum packaging) retards the progress of lipid oxidation (17). Lacroix *et al*. (3) showed that the antioxidant properties of thyme and rosemary (marinade) reduce the generation of initial free radicals in the FA and cause a substantial reduction in volatile hydrocarbons generated between 3 and 9 kGy radiolysis of unsatured FA. The off-odor detected on treated samples is due to the production during irradiation of some small M.W. volatile compounds, which are also pro-

TABLE 5
Regression Coefficients for Equations Relating the Concentration (%) of Linoleic Acid (PL) and (%) Linolenic Acid (PL) in Chicken Legs Irradiated in Air, Vacuum, or Marinade to Radiation Dose and Storage Time

FA	Constant	Radiation dose (kGy)	Storage time at 4°C (d)	R^2
$C_{18:2}$ (air)	16.951	–0.504[a]	–0.106[a]	0.93
$C_{18:2}$ (vacuum)	18.717	–0.415[a]	–0.092[a]	0.95
$C_{18:2}$ (marinade)	18.577	–0.126[a]	–0.067[a]	0.90
$C_{18:3}$ (air)	0.651	–0.063[a]	–0.023[a]	0.78
$C_{18:3}$ (vacuum)	0.803	–0.046[a]	–0.036[a]	0.86
$C_{18:3}$ (marinade)	1.101	–0.083[a]	–0.049[a]	0.82

[a]$P \leq 0.01$. For abbreviation see Table 2.

TABLE 6
Treatment Means[a] for the Sensory Quality of Irradiated Chicken Legs

		Sensory attributes			
Treatments		Color[b] intensity	Odor[c] intensity	Flavor[d] intensity	Muscle fiber[e] integrity
Air					
	Control	6.1 ± 2.9A	6.1 ± 2.3A	6.9 ± 2.1A	6.2 ± 2.9A
	Irradiated (5 kGy)	6.1 ± 2.8A	7.8 ± 1.4B	8.7 ± 1.8B	7.7 ± 2.1A
Vacuum					
	Control	8.8 ± 3.1A	9.1 ± 2.4A	8.7 ± 2.4A	8.4 ± 2.1A
	Irradiated (5 kGy)	8.7 ± 2.8A	8.4 ± 2.8A	8.1 ± 2.9A	7.9 ± 2.8A
Marinade					
	Control	7.8 ± 2.1A	8.5 ± 2.7A	8.9 ± 1.6A	8.9 ± 1.4A
	Irradiated (5 kGy)	7.7 ± 2.3A	8.1 ± 2.1A	8.2 ± 2.1A	8.1 ± 2.7A

[a]No significant difference ($P > 0.05$) between means in a column bearing the same letter. Panelists ($n = 10$) evaluated the samples using a 15-cm line scale.
[b]Scale of 0 = pale yellow to 15 = dark yellow.
[c]Scale of 0 = none to 15 = strong.
[d]Scale of 0 = no off-flavors to 15 = intense off-flavors.
[e]Scale of 0 = tough to 15 = tender.

duced by free radical-mediated autoxidation. The overall acceptability decreased with increasing dose. Low-dose irradiation is associated with insignificant changes in proteins, amino acids, and fats, and at 2.5 kGy there are negligible changes in the odor or taste of the product (18). In general, when a dose of 2.5 kGy is used, no change can be perceived before or after cooking the meat by roasting and on storage at 1 to 4°C. Upon increasing the dose to 5 kGy, the observed initial radiolytic odor disappears on storage at 1 to 4°C and roasting of the meat (7).

Irradiation enhances lipid oxidation. Marinating, however, has the potential to control oxidation of unsaturated FA in chicken, particularly those derived from the PL. Irradiation of raw chicken, in air or under vacuum, favors oxidation of unsaturated FA into lower-carbon-number saturated FA. A combination of marinating and vacuum packaging might be a better alternative for controlling oxidation/degradation of high-carbon-number unsaturated FA during irradiation of chicken.

ACKNOWLEDGMENTS

The authors are grateful to MDS Nordion International Inc. for the irradiation treatments of the chicken legs. This research was supported by INRS-Institut Armand-Frappier, Laval, Québec, Canada, and a fellowship grant from the International Atomic Energy Agency of the United Nations.

REFERENCES

1. Dziezak, J.D., Antimicrobial Agents, *Food Technol. 40*:104–111 (1986).
2. Wu, J.W., M.H. Lee, C.T. Ho, and S.S. Chang, Elucidation of the Chemical Structures of Natural Antioxidants Isolated from Rosemary, *J. Am. Oil Chem. Soc. 59*:339–345 (1982).
3. Lacroix, M., W. Smoragiewicz, L. Pazdernik, M.I. Koné, and K. Krzystyniak, Prevention of Lipid Radiolysis by Natural Antioxidants from Rosemary (*Rosmarinus officinalis* L.) and Thyme (*Thymus vulgaris* L.), *Food Res. Int. 30*:457–462 (1997).
4. Deighton, N., S.M. Glidewell, S.G. Deans, and B.A. Goodman, Identification by EPR Spectroscopy of Carvacrol and Thymol as the Major Sources of Free Radicals in the Oxidation of Plant Essential Oils, *J. Sci. Food Agric. 63*:221–225 (1993).
5. Thayer, D.W., Y. Cathleen, D. Dickerson, R. Ramkishan, G. Boyd, and B.C. Chandramohan, Destruction of *Salmonella typhimurium* on Chicken Wings by Gamma Radiation, *J. Food Sci. 57*:586–589 (1992).
6. Merritt, C.P., P. Angelini, E. Wierbicki, and G.W. Shults, Chemical Changes Associated with Flavor in Irradiated Meat, *J. Agric. Food Chem. 23*:1037–1041 (1975).
7. Lacroix, M.L., M. Jobin, S. Hamel, V. Stahl, M. Gagnon, and C. De Couvercelle, Effects of 3 kGy and 7 kGy Gamma Radiation Doses on Odour and Flavour of Fresh Chicken Breast, *Microbiol. Aliments Nutr. 9*:375–379 (1991).
8. Hanis, T., P. Jelen, P. Klir, J. Mnukova, B. Perez, and M. Pesek, Poultry Meat Irradiation. Effect of Temperature on Chemical Changes and Inactivation of Microorganisms, *J. Food Prot. 52*:26–29 (1989).
9. Katta, S.R., D.R. Rao, G.R. Sunki, and C.B. Chawan, Effect of Irradiation of Whole Chicken Carcasses on Bacterial Loads and Fatty Acids, *J. Food Sci. 56*:371–372 (1991).
10. Maxwell, R.J., W.N. Marmer, M.P. Zubillaga, and G.A. Dalickas, Determination of Total Fat in Meat and Meat Products by a Rapid Dry Column Method, *J. Assoc. Off. Anal. Chem. 63*:601–602 (1980).
11. Salih, A.M., D.M. Smith, J.F. Price, and L.E Dawson, Modified Extraction *z*-Thiobarbituric Acid Method for Measuring Lipid Oxidation in Poultry, *Poult. Sci. 66*:1484–1488 (1987).
12. Slover, H., and E. Lanza, Quantitative Analysis of Fatty Acids by Capillary Gas Chromatography, *J. Am. Oil Chem. Soc. 56*:933–943 (1979).
13. Poste, L.M., D.A. Mackie, G. Butler, and E. Larmond, *Laboratory Methods for Sensory Analysis of Food*, Agriculture Canada, Ottawa, 1991, pp. 1–87.
14. Rady, A.M., R.J. Maxwell, E. Wierbicki, and J.G. Phillips, Effect of Gamma Radiation at Various Temperatures and Packaging Conditions on Chicken Tissues. I. Fatty Acid Profiles of Neutral and Polar Lipids Separated from Muscle and Skin Irradiated at −20°C, *Radiat. Phys. Chem. 31*:195–202 (1988).
15. Love, J.D., and A.M. Pearson, Lipid Oxidation in Meat and Meat Products—A Review, *J. Am. Oil Chem. Soc. 48*:547–549 (1971).
16. Hassan, I.M., A.A. Mahmoud, and R.A. Hegazy, Changes in Fatty Acids Composition Accompanying Cold and Freezing Storage of Irradiated Chicken, *Annals Agric. Sci. 33*:1179–1199 (1988).
17. Hall, K.N., M.B. Fey, G.J. Buonopane, R.G. Jensen, and E. Wierbicki, Effect of Irradiation, Packaging and Antioxidants on the Concentration of Monocarbonyls in Chicken Rolls, *Proceedings of the European Meeting of Meat Research Workers 1*:225–228 (1980).
18. Urbain, W.M., Radurization and Radicidation: Meat and Poultry, in *Preservation of Food by Ionizing Radiation*, edited by E.S. Josephson and M.S. Peterson, CRC Press, Boca Raton, 1983, Vol. 3, pp. 1–11.

[Received May 14, 2002; accepted March 3, 2003]